NEW SERDP Project: Copper-Beryllium Alternatives Alloys Development

Project Number : WP2138

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Performers

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Northrop Grumman Corporation

Solidification and phase transformation, metallics processing, and system integration

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QuesTek Innovations

Computer aided modeling of alloy phase transformations and kinetics , and the practical application of models to materials system design.

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University of Florida

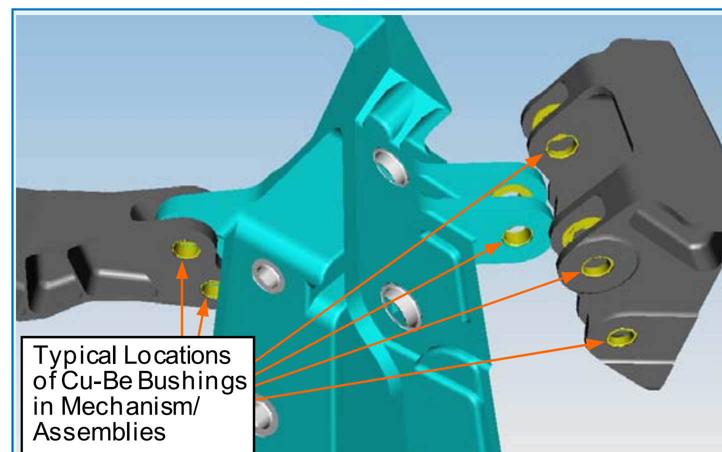
Analysis and characterization of wear mechanisms

Problem Statement

• **Copper-Beryllium (Cu-Be) alloys extensively employed for highly loaded airframe wear applications (approaching σ_{UTS} < 175 ksi)**

• **Health risks associated to beryllium exposure and increasingly more stringent regulations resulted in significant design, cost, manufacturing, and sustainment challenges, as well as performance limitations.**

• **New, alternative alloys are required to fulfill this unique performance requirement thus supporting new platform development as well as fleet supply\manufacturing and sustainment.**



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Northrop Grumman Clearance Approval#: 11-0061

Technical Objective

• Develop and characterize alloy\processing route for Cu-Be alloy replacement in highly loaded wear applications.

• Development bushing designs for the enhancement of dynamic wear performance.

• Demonstration of new material\processing route and design in a full scale representative environment

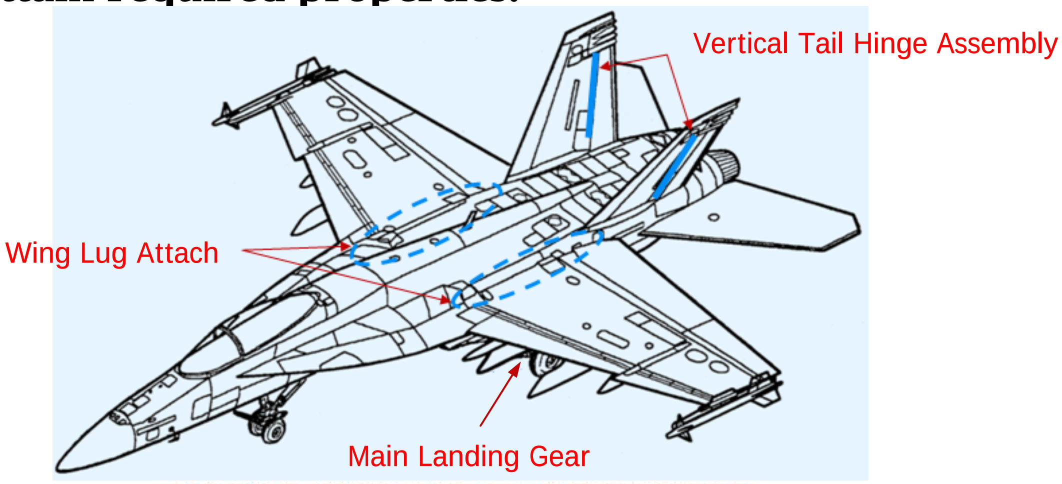
• Execution of production as well as Environmental, Health and Safety impact assessment

Technical Background

Unique balance of static strength and wear resistance required for highly loaded bushing\bearing applications

• **Commercially available alloys including high strength Cu-based and Co-based alloy systems have been previously investigated, demonstrated ability to approach design and performance needs from strength standpoint, but have fell short in performance.**

• **Computational toolset available to evaluate this class of alloys for further optimization to attain required properties.**

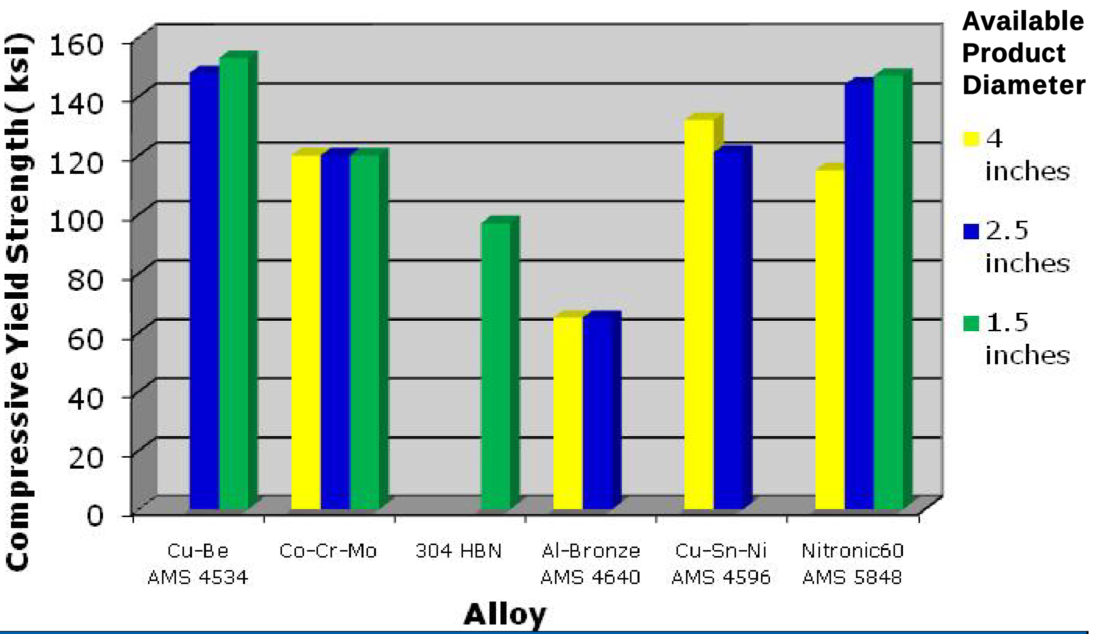


Technical Background

Considerable evaluation previously conducted via previously executed programs.

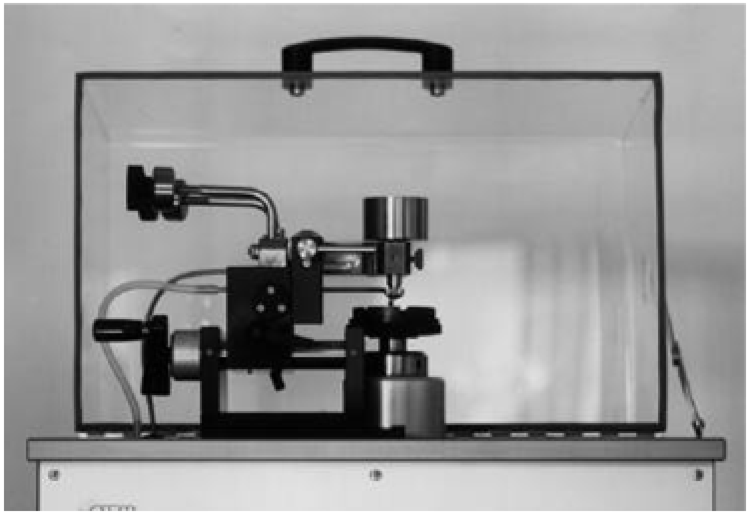
- **Materials investigated included Al-bronze, Cu-Sn-Ni, Co-Cr-Mo, Nitronic60, HBN 304 stainless steel, as well as low friction coating\liner systems on PH stainless steel substrates**

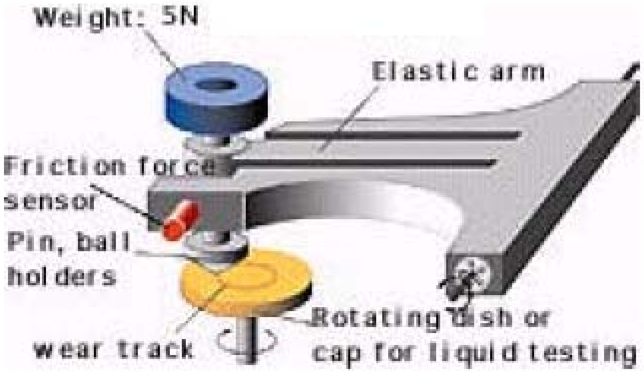
- **Compression strength and wear resistance (COF, wear rate, galling resistance) were employed as primary design drivers**



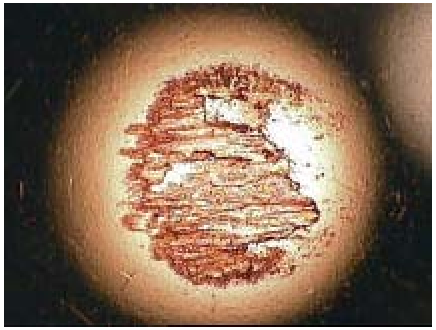
No Cu-Be Alternative Currently Exists Which Satisfies All Size Needs For Current Aircraft Design

Technical Background

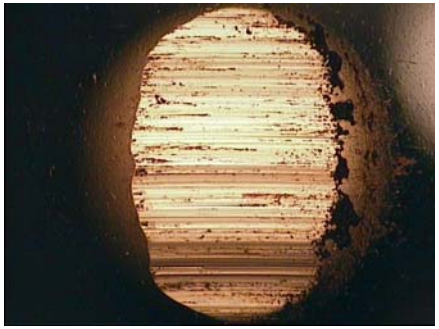




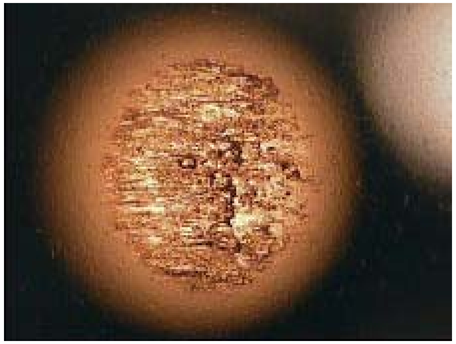
Wear resistance evaluated as a function of response in sliding frictional environments



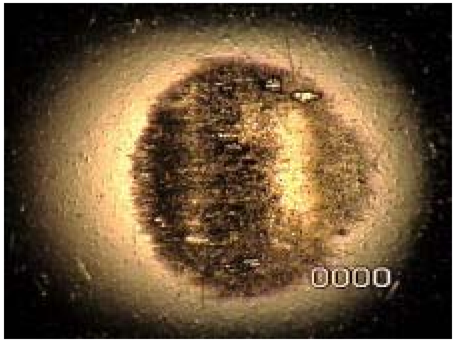
Cu-Be
AMS 4534



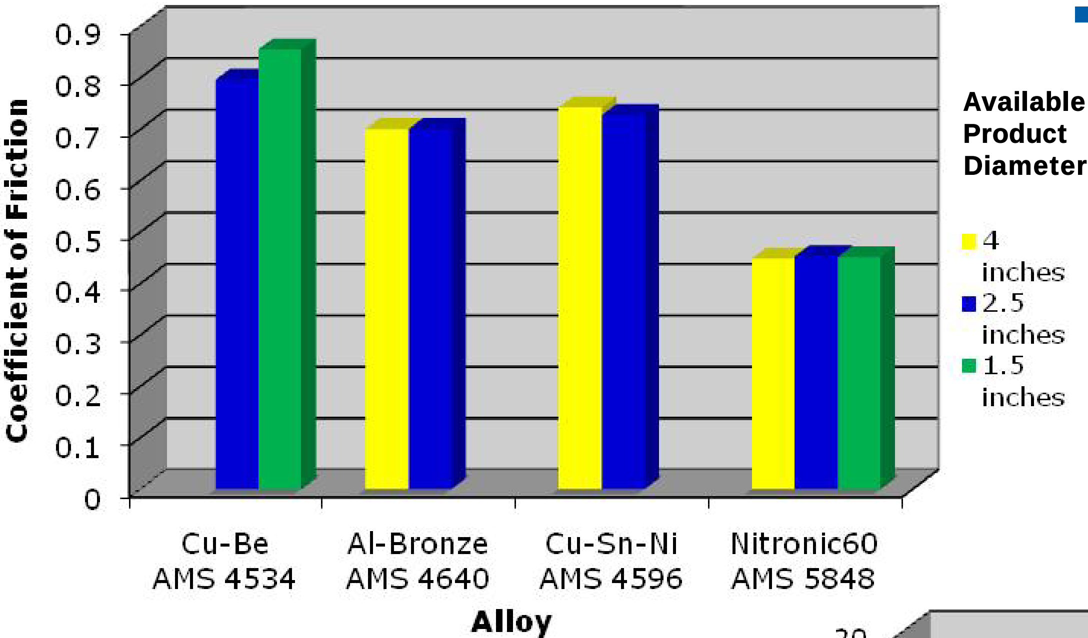
Al-Bronze



Cu-Sn-Ni
AMS 4596



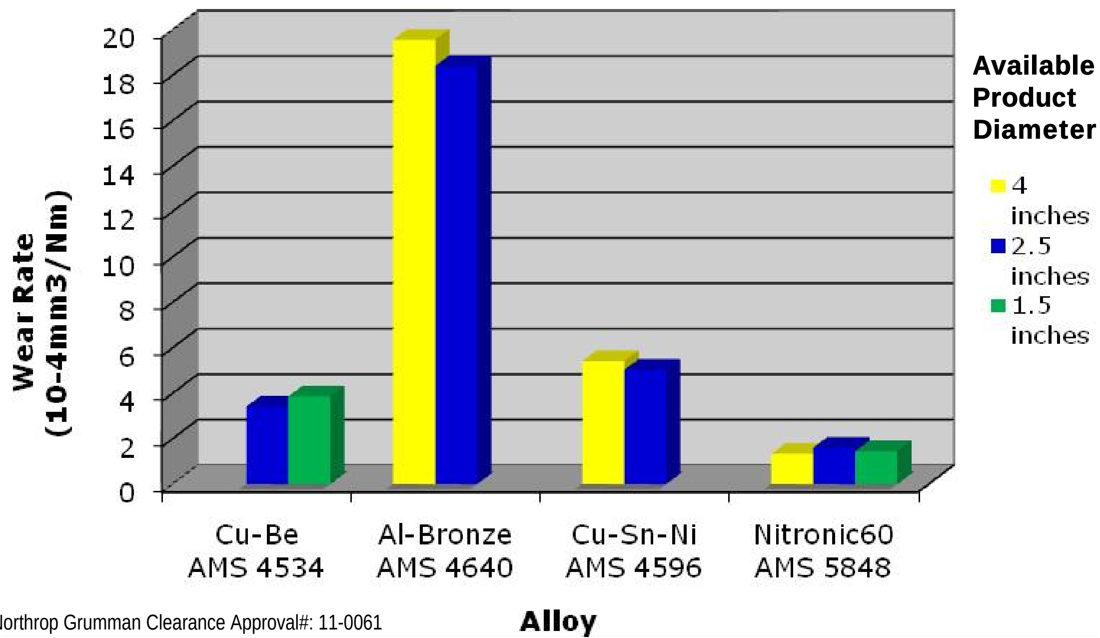
Nitroniv60
AMS 5848



•Several alloys yielded promising results

- Cu-Sn-Ni 135 ksi
- Co-Cr-Mo 140 ksi
- Nitronic60

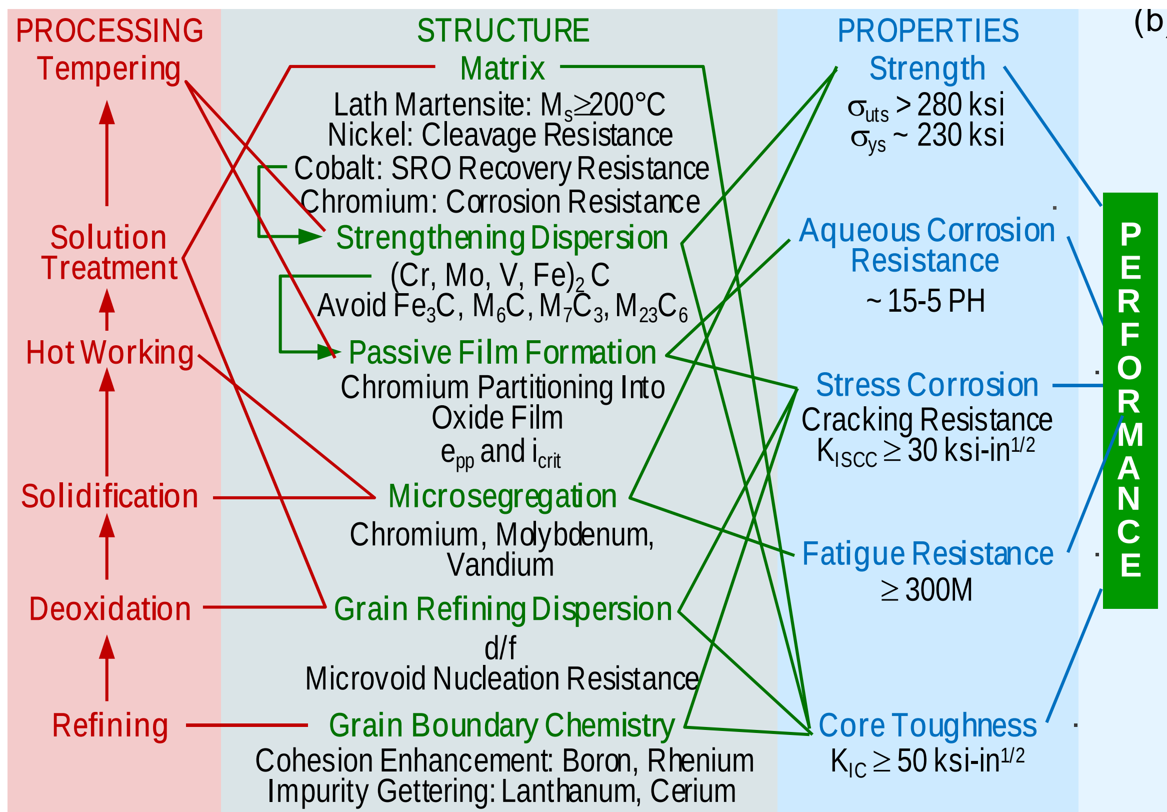
• No direct Cu-Be alternative identified for all size ranges required



Technical Background

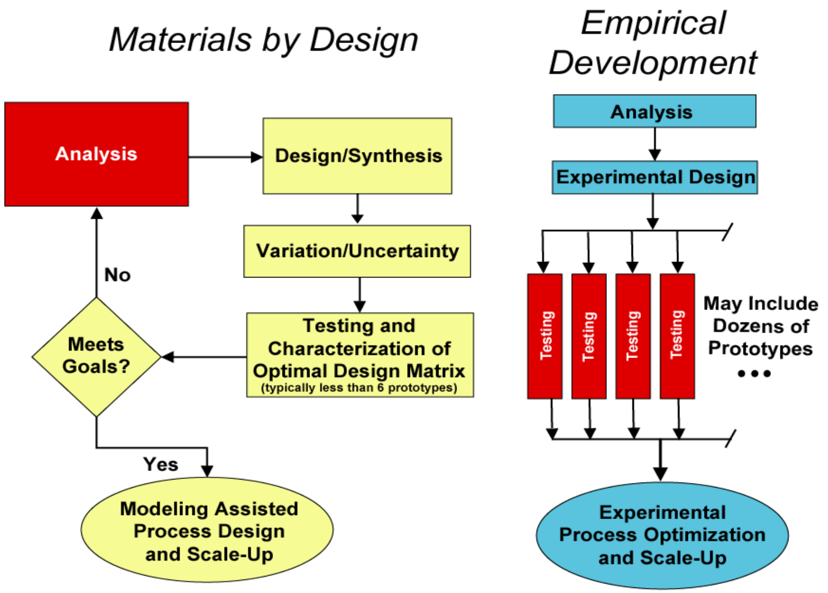
Alloy\processing route design methodology and computational toolset available to evaluate these class of alloys for further optimization to attained required strength performance

- **QuesTek's Materials by Design® development methodology has been proven in previous materials development programs (Ferrium S53).**



Technical Background

- **Ferrium S53 development highlights:**
  - UHS corrosion-resistant drop-in replacement for 300M to eliminate the need for toxic cadmium (Cd) coatings on landing gear components
  - Dec 99 – SERDP SEED Program starts
  - June 01 – SERDP Phase II Program starts
  - March 03 – ESTCP LG Program starts
  - June 06 – ESTCP RGA Program starts
  - Dec 08 – DoD Corrosion Resistant LG Cooperative Program starts
  - May 13th, 2010– T38 Flight Approval
  - T38 MLG First Flight Scheduled for 4th Quarter 2010.



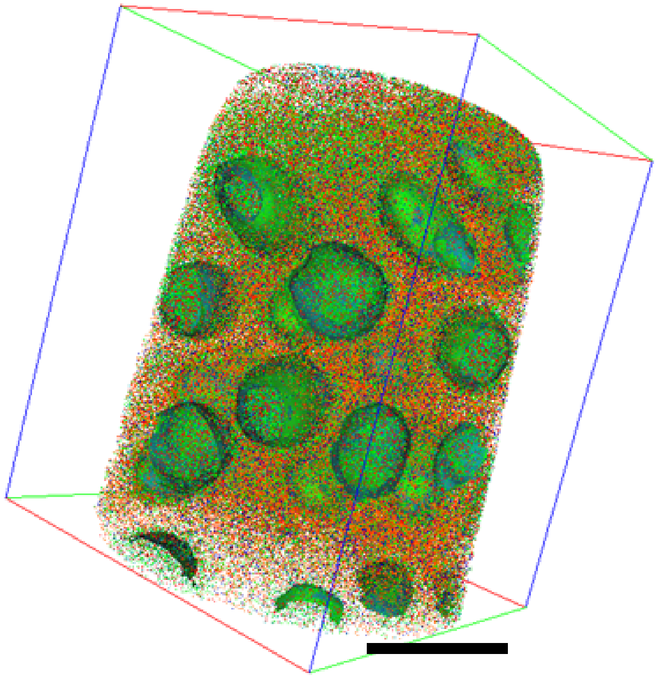
Note: the boxes in red represent the primary focus of the effort

Technical Background

• **Thermodynamic and kinetic tools computational tools developed and demonstrated by QuesTek in previous work will be employed and form basis for alloy design and process development**

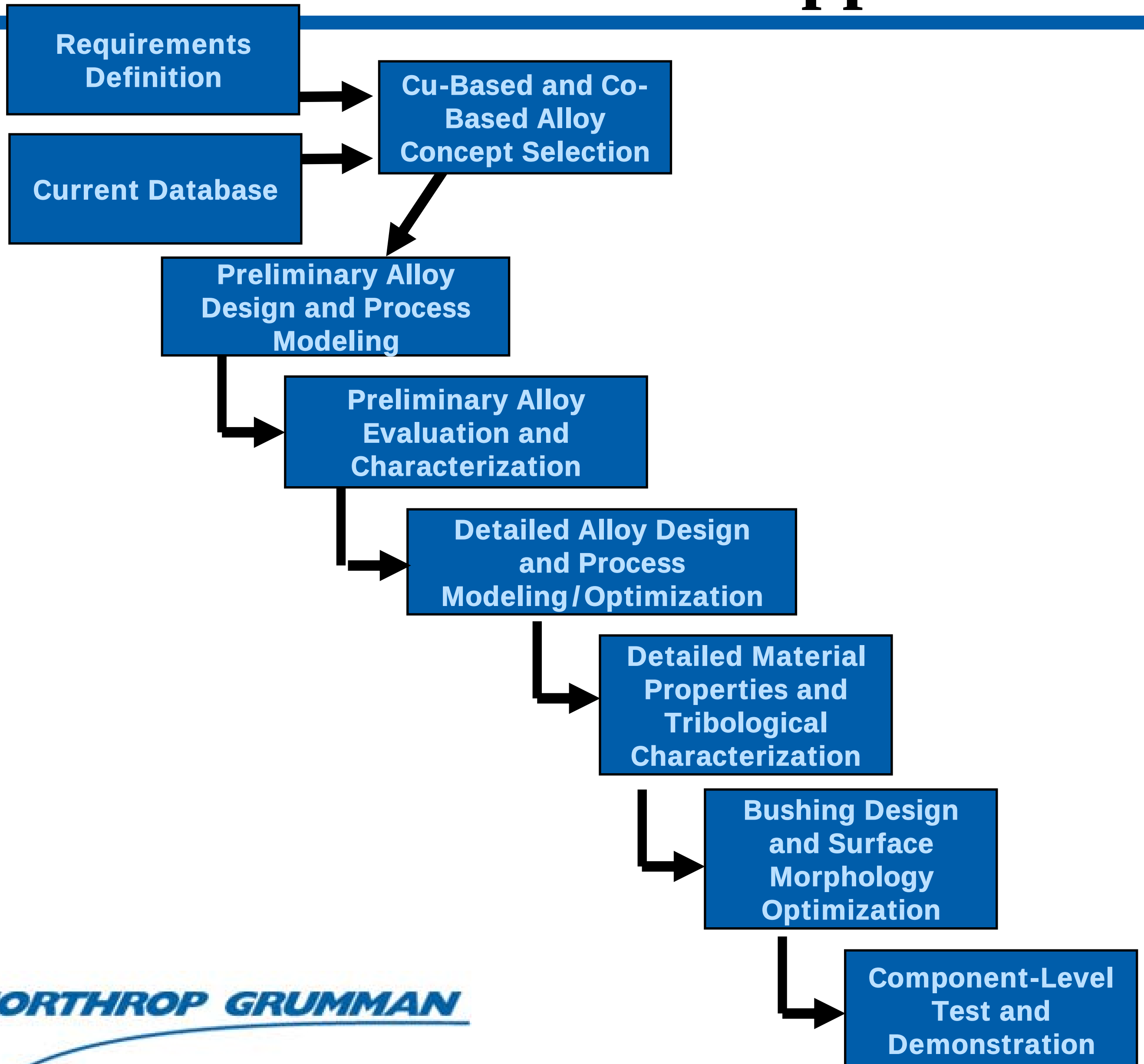
- **Solidification and secondary phase strengthening precipitation of nanoscale $L1_2$ coherent particle formation prediction in FCC matrices**

- **Co-based alloy specific thermodynamic and processing computational modeling tools also currently being developed and will be employed**



Local Electrode Atom Probe reconstruction of a high-strength Cu-based alloy designed using QuesTek's *Materials by Design* process to incorporate nano-scale $L1_2$ strengthening particles

Technical Approach



Technical Approach

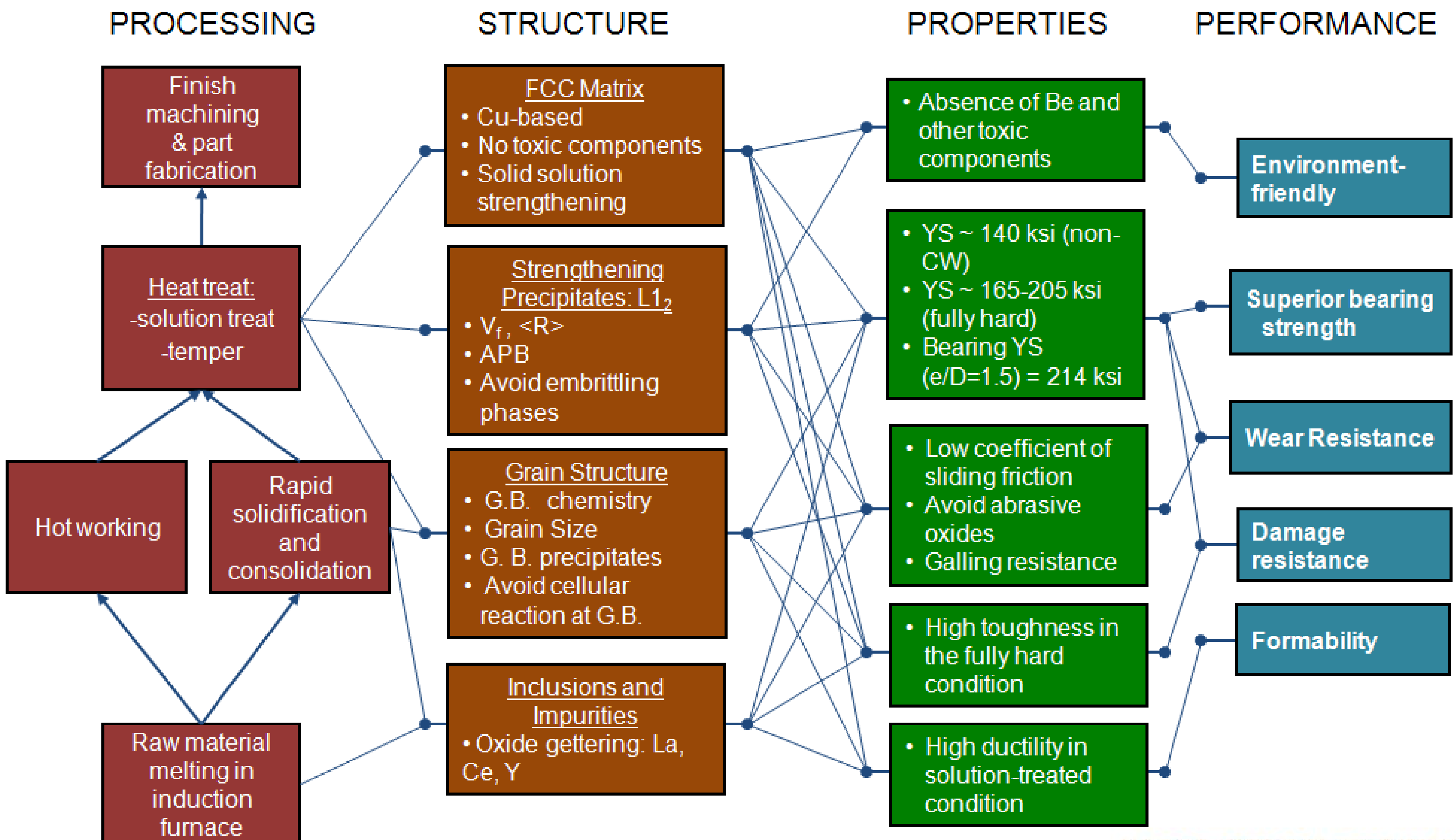
Alternative Copper-Beryllium Concept Selection

- Refine\revise design requirements for greatest impact on implementation
  - Primarily compressive yield, wear resistance (including galling and fretting resistance)
  - Stiffness, density, and corrosion resistance also considered

- Identify Cu- and Co-Based alloys for further investigation in following task.

Technical Approach

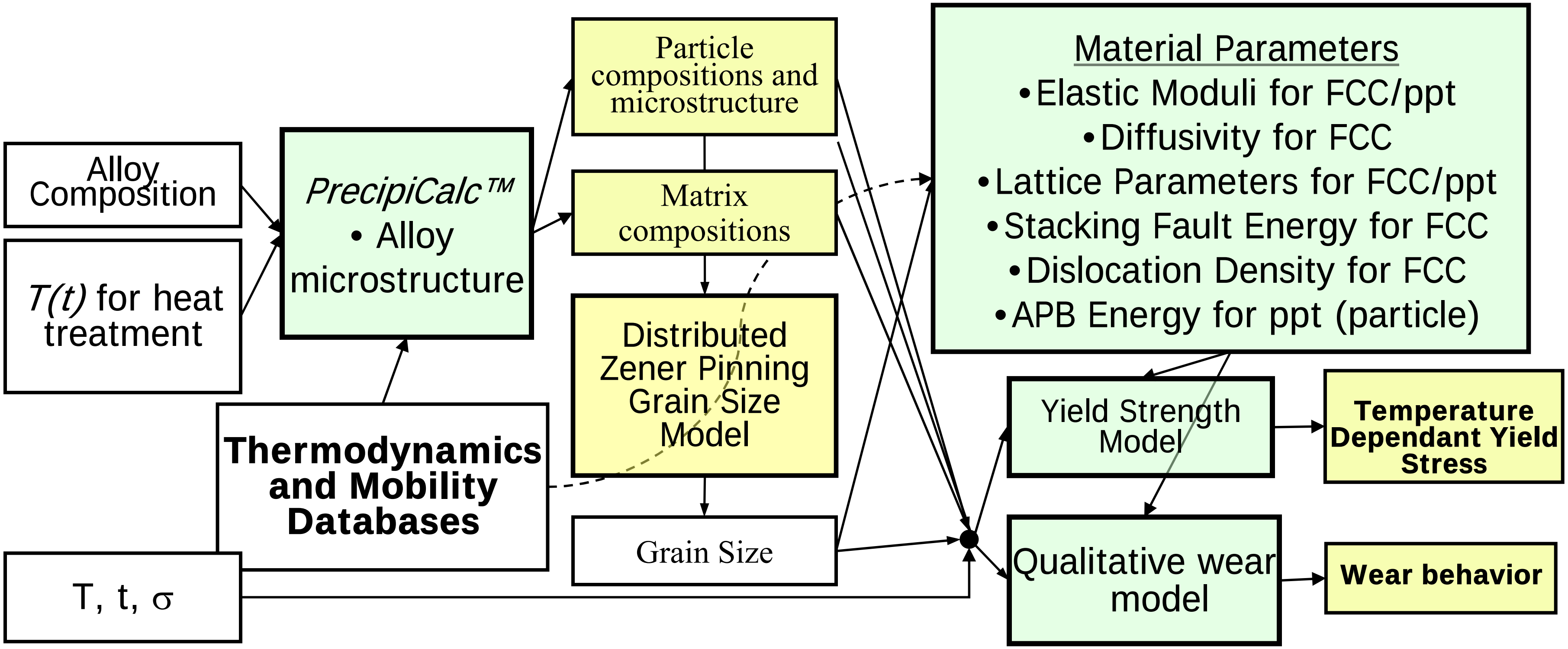
Preliminary Alloy Design and Process Modeling



Flow block diagram

Technical Approach

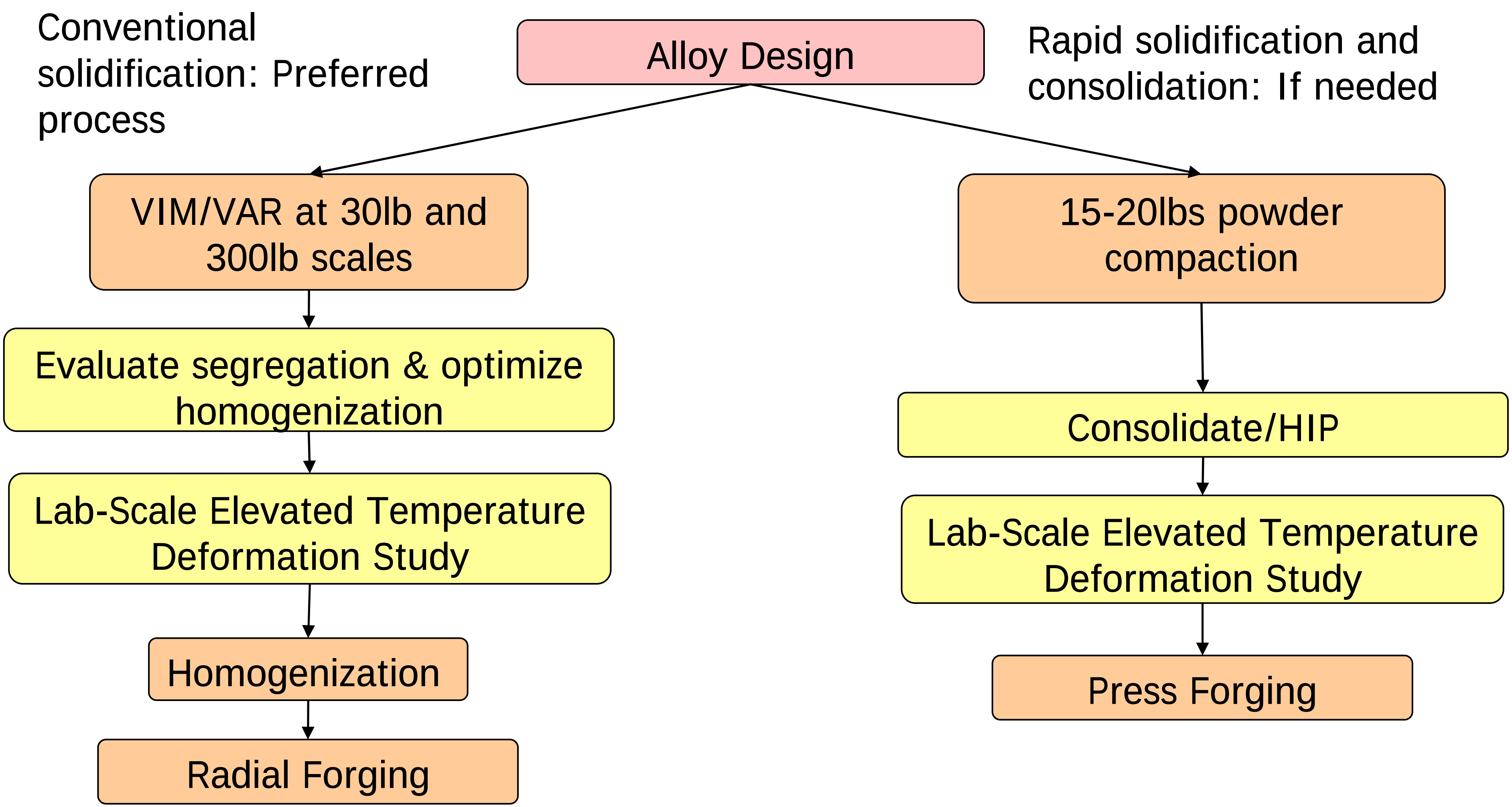
Preliminary Alloy Design and Process Modeling



With minor modification, QuesTek 's in-house thermodynamic and kinetic databases for copper and cobalt-based systems can be employed

Technical Approach

Prototyping strategy for initial and secondary alloy production



Technical Approach

Preliminary Cu-Be Alternative Alloy Evaluation and Characterization

• Execute static mechanical properties evaluation and preliminary wear characterization of Cu- and Co-based alloys post computational modeling and alloy production; compare baseline AMS 4534 Cu-Be to Cu- and Co-based alternatives.

• The initial criteria for screening will be static compression and pin-on-disk wear testing (friction coefficient and wear rate determination in dry sliding conditions against representative steels).

- Compression testing from each of the Cu- and Co-based alloys will be performed per ASTM E 9
- Pin-on-Disk test per ASTM G 99 will be comprised of two loading conditions for each of the Cu- and Co-based alloys

Technical Approach

Preliminary Cu-Be Alternative Alloy Evaluation and Characterization

• Go\No-Go: Data must show enhancement of one of the two candidate Cu-Be alternative alloys to justify downselection and further investigation via secondary alloy design and process modeling.

- Must indicate improvement of compression strength at minimum

• Surface characterization of candidate materials post wear tests will also be performed to evaluated fretting\galling propensity.

• The body of data generated will be employed for further calibration of computational modeling tools and selection of final alloy for development consideration from the two screened.

Technical Approach

Detailed Alloy Design and Process Modeling

• The computational models will be calibrated from the data generated in the previous initial Cu-Be alternative alloy evaluation and characterization task.

• The process executed in the initial alloy design and process modeling phase will be then be repeated on the downselected material to further refine, and optimize alloy composition and processing route.

Technical Approach

Detailed Material Properties and Tribological Characterization

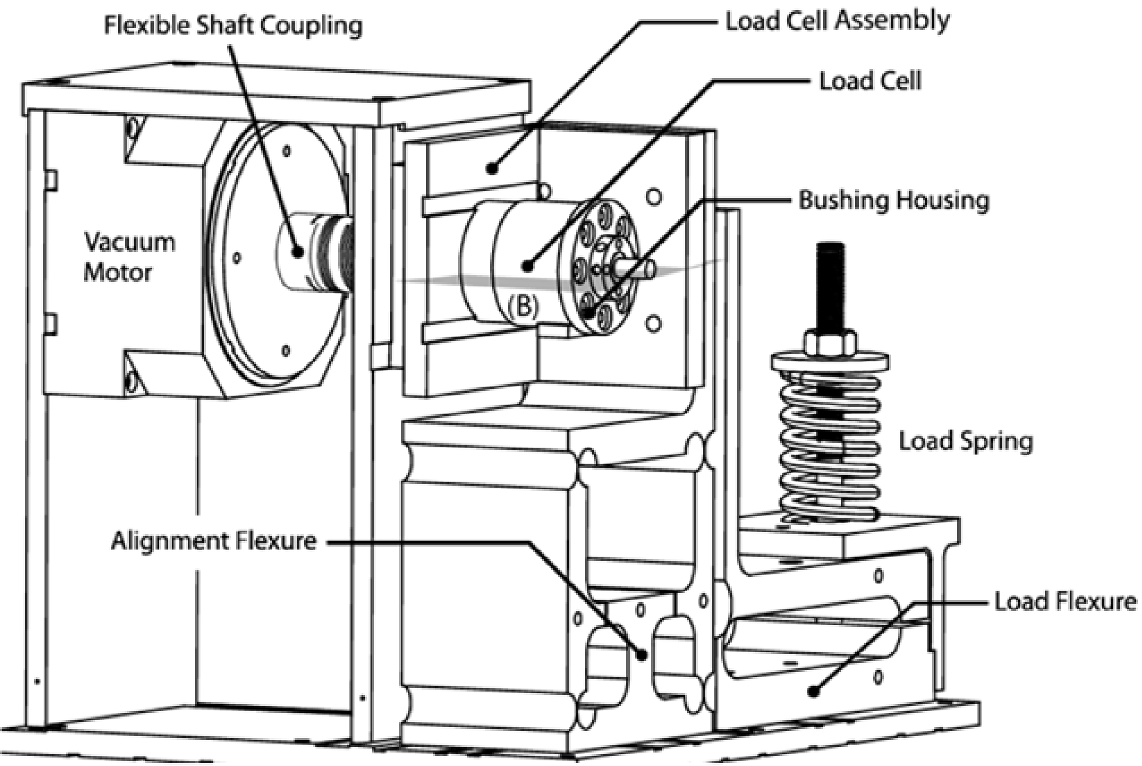
- **An expanded static and dynamic mechanical properties evaluation and comprehensive wear characterization of the downselected Cu- or Co-based alloys will be conducted**

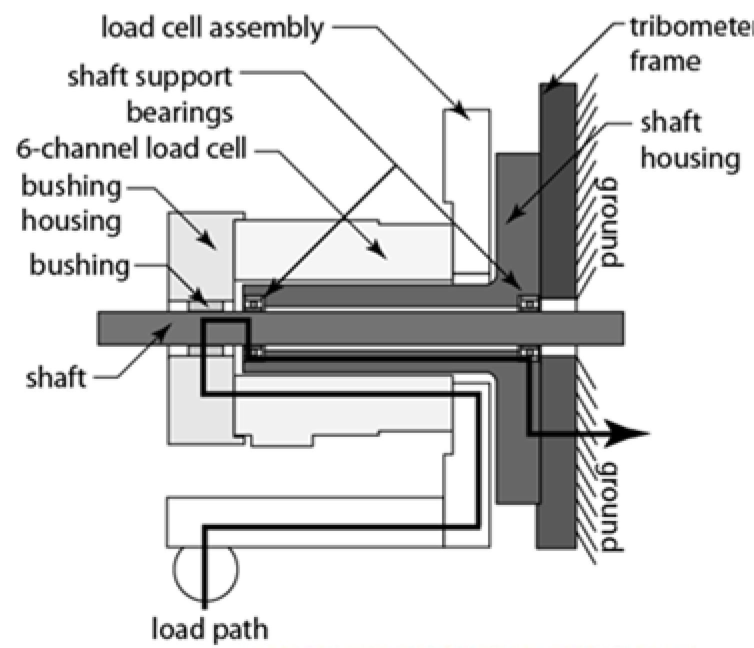
- **The criteria for evaluation in this task will be static compression and tension, strain life fatigue, and pin-on-disk wear testing (friction coefficient and wear rate determination in dry sliding conditions against representative steels), and galling threshold.**
  - **Compression testing per ASTM E 9**
  - **Tension testing) per ASTM E 8**
  - **Pin-on-Disk test per ASTM G 99 will be comprised of two loading conditions**
  - **Galling threshold per ASTM G 98 will be comprised of varying loading conditions to identify galling threshold stress**

Technical Approach

Detailed Material Properties and Tribological Characterization

- **Sub-component level wear testing will be conducted to further characterize bushing performance**

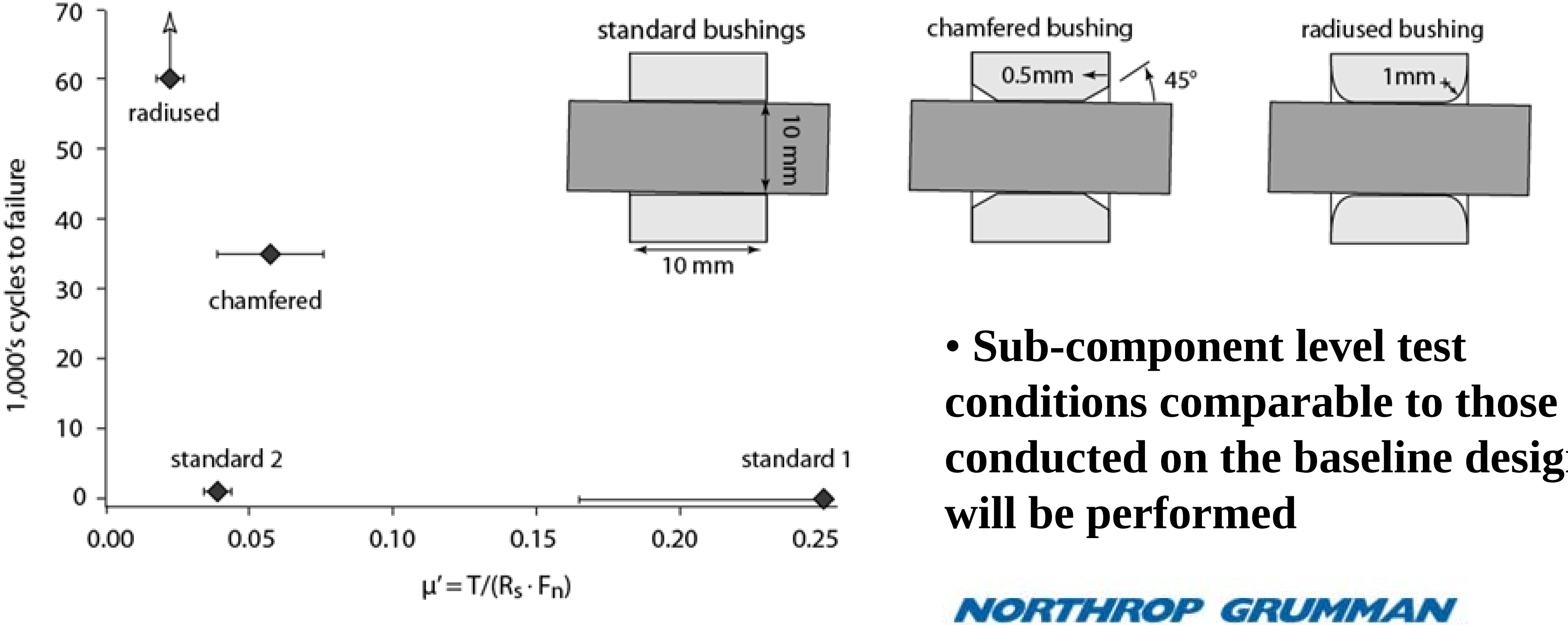




Technical Approach

Bushing Design and Surface Morphology Optimization

• **Novel, superior bushing designs and surface conditions will be developed and characterized to enhance the performance of the alloy and processes identified in previous tasks**



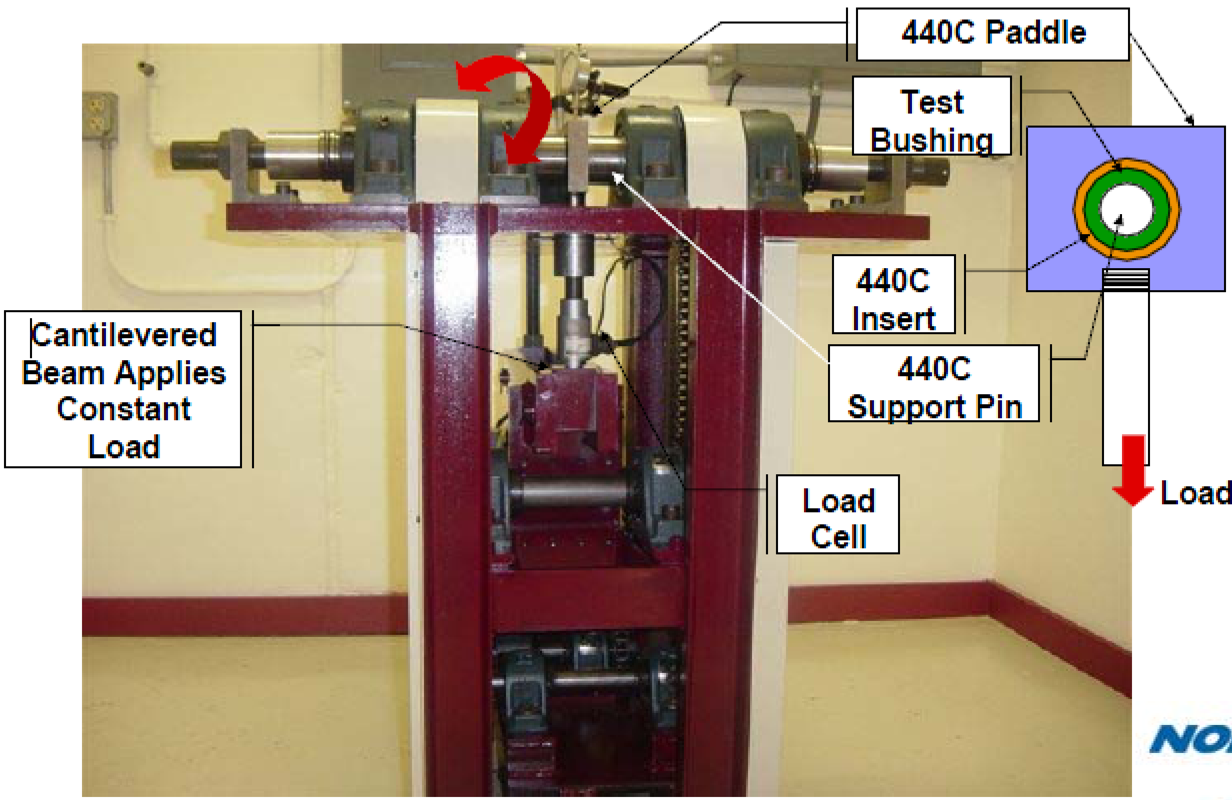
Thousands of cycles to failure plotted versus friction coefficient (μ') for standard and edge modified bushings.

• **Sub-component level test conditions comparable to those conducted on the baseline design will be performed**

Technical Approach

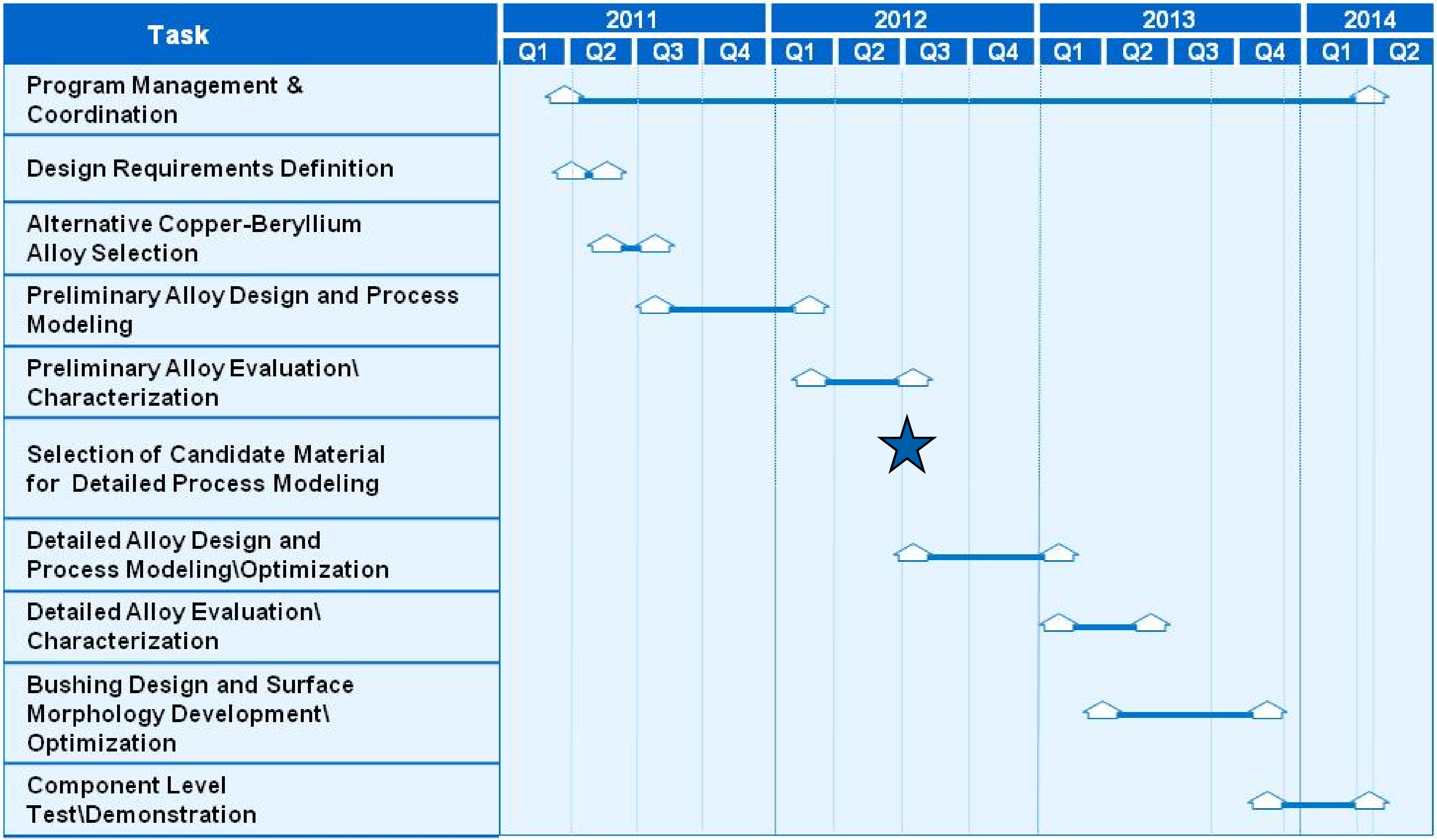
Component-Level Test and Demonstration

• **Full-scale SAE AS81820 testing of bushings will be conducted to demonstrate performance under high loading conditions identified in requirement definition task at the onset of the program**



•**Full scale tests will be performed on baseline Cu-Be, alternative alloy\processing with baseline design and alternative alloy\processing with alternative bushing design.**

Overall Project Plan



GO/NO GO Decision: ★ **Must show enhancement to justify further investigation via secondary alloy design and process modeling. Must indicate improvement of compression strength at minimum.**

Deliverables

- **Preliminary static and dynamic properties design dataset for alternative Cu-Be alloys**
  - **Tensile ASTM E 8**
  - **Compression ASTM E 9**
  - **Strain-Life Fatigue ASTM E 606**
  - **Galling Threshold ASTM G 98**
  - **Pin-on-Disk Wear ASTM G 99**

- **Novel bushing design for enhanced performance**

- **Full scale demonstration**
  - **Alloy\processing route performance**
  - **Bushing Design performance**

- **Refined computational toolset for the prediction of Cu- and Co-based alloy properties on the basis of composition and processing**

Questions?

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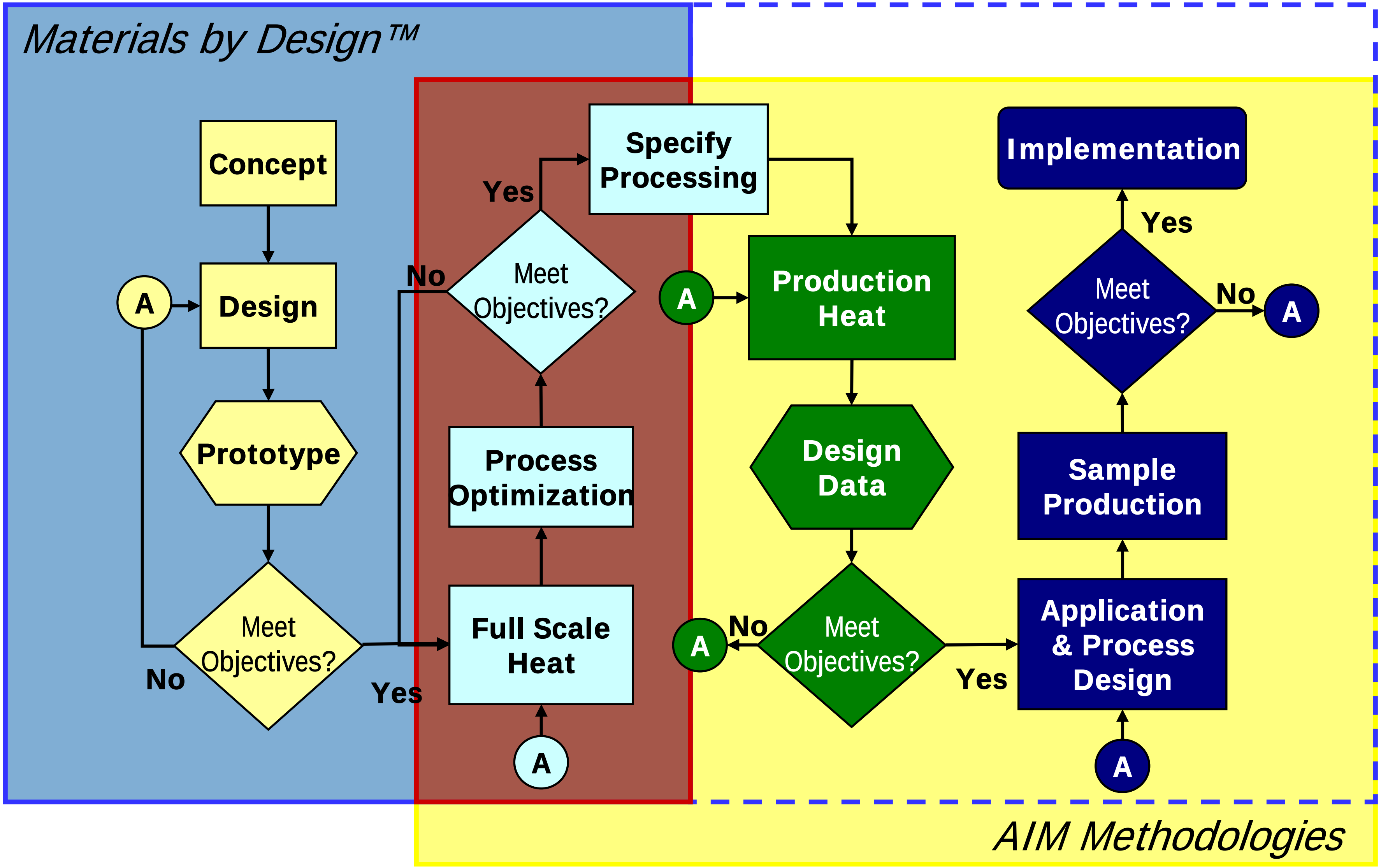
Backup Slides

Supporting material

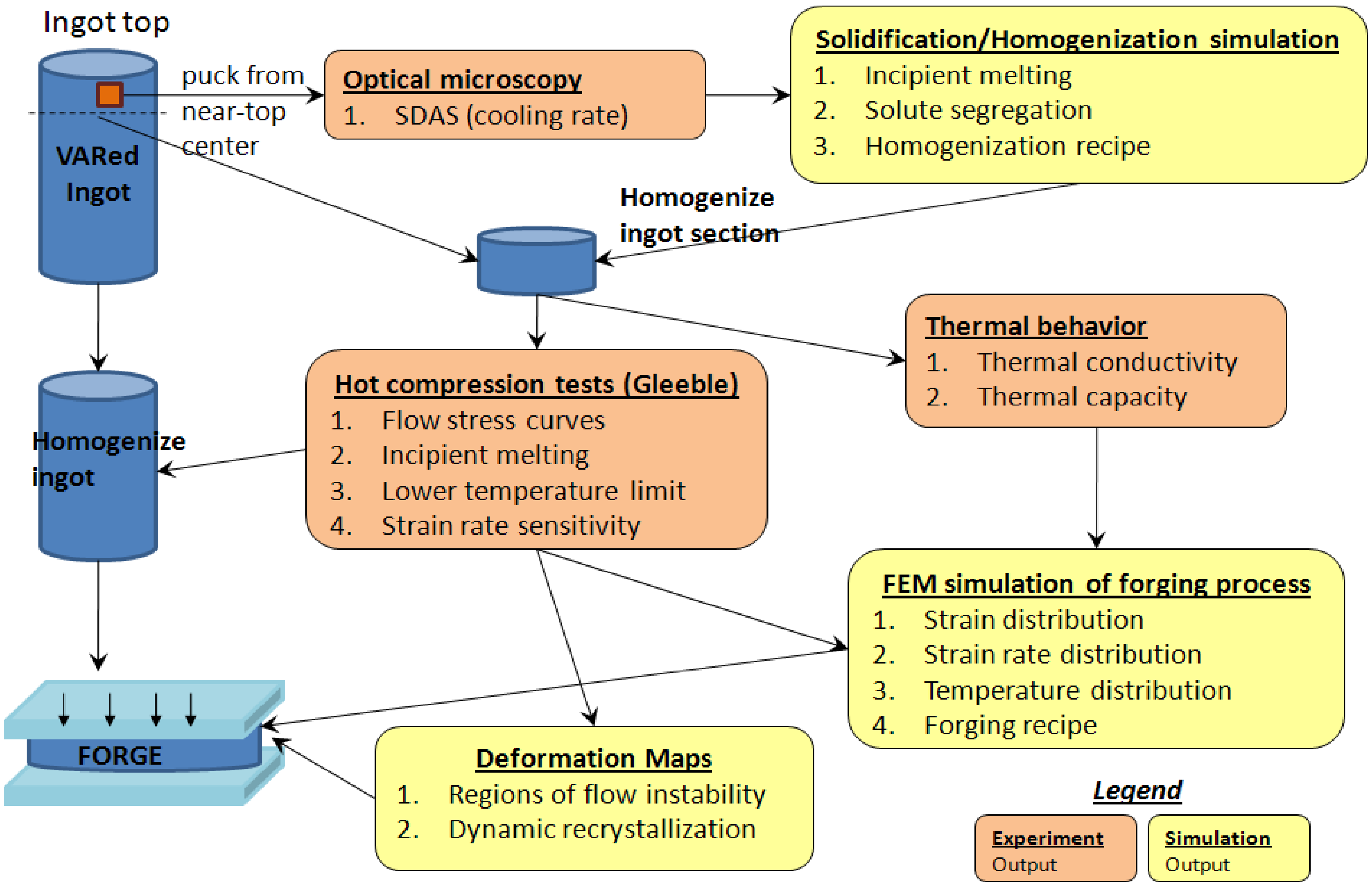
Transition Plan

Secondary Alloy Design and Process Modeling/Optimization



ICME-based Process Optimization

Modeling and efficient experimentation



- Moving boundary simulations to design optimal homogenization process
- FE simulations to optimize forging recipe

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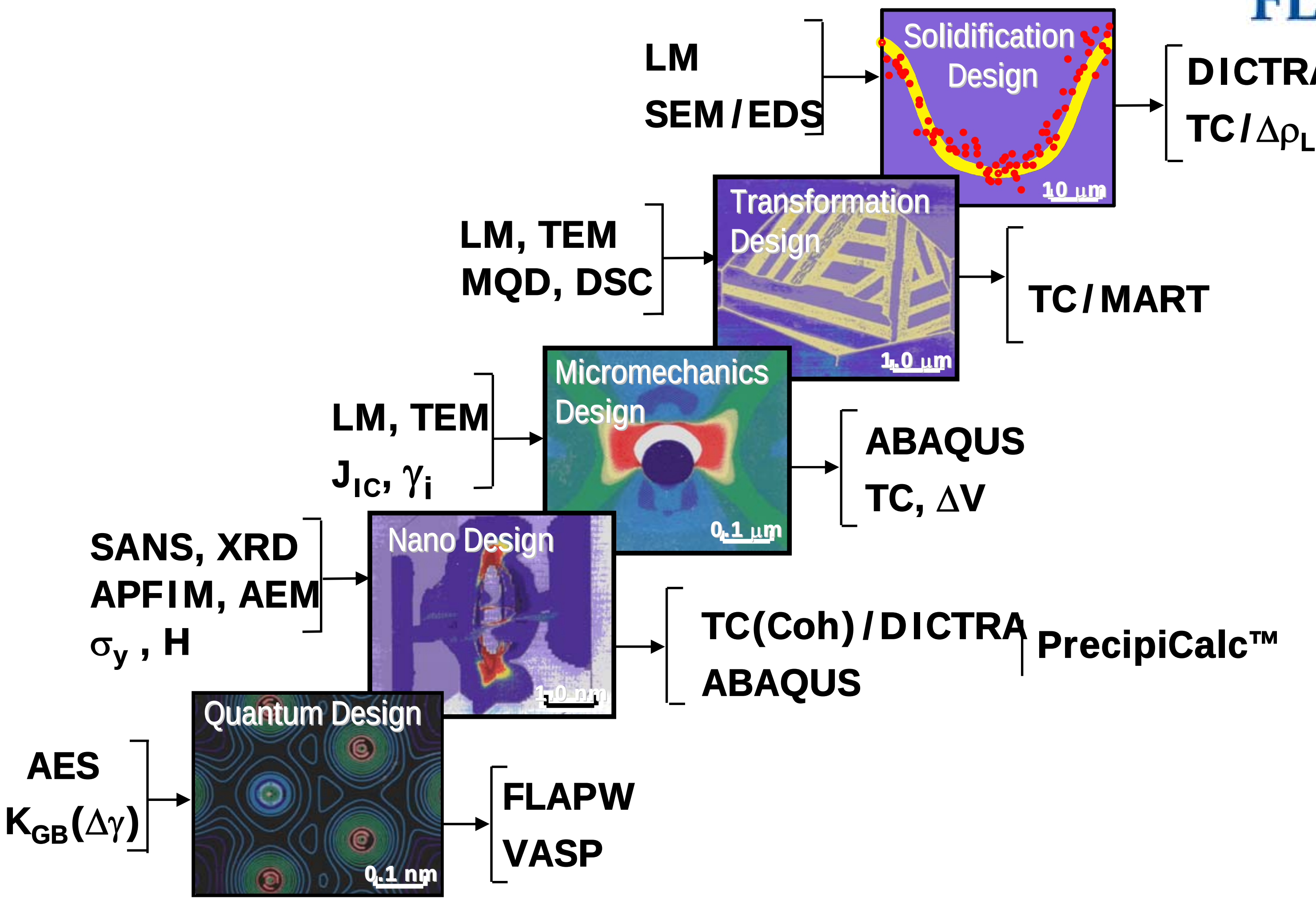
Hierarchy of Design Models

UNIVERSITY of FLORIDA



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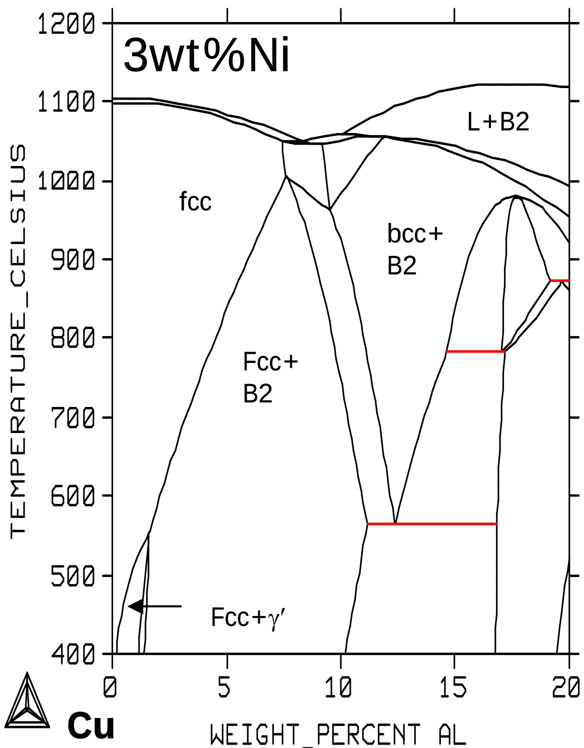
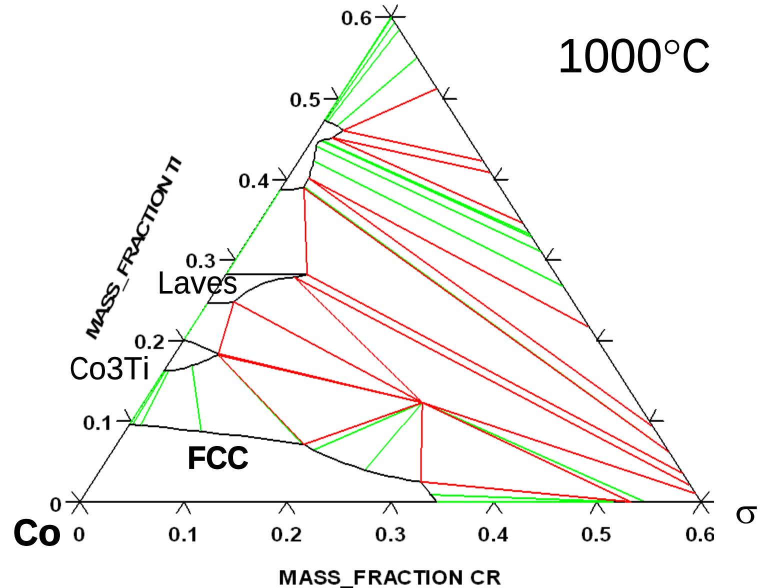
Thermodynamic Databases

QuesTek has in-house thermodynamic databases for copper and cobalt-based systems that can be used for CALPHAD-based microstructure design





Example outputs from QuesTek's thermodynamic databases for Cu and Co-based systems

Design Guidelines for Wear

1. The friction coefficient increases as the work of the adhesion, W_{ad}, increases. To minimize work of adhesion, alloy surface free energy should be low.

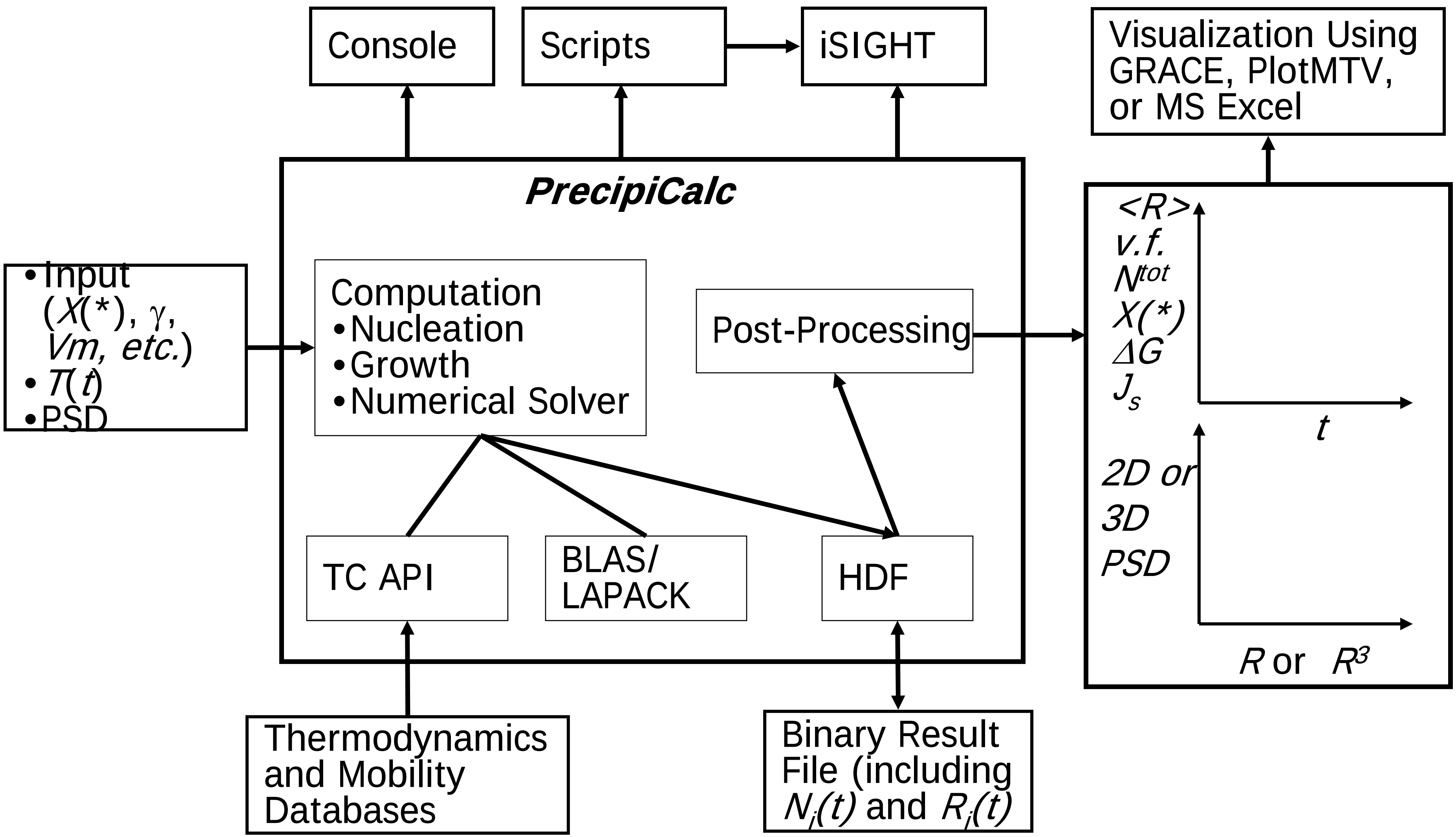
2. Wear debris: The size, shape, and thermo-mechanical properties of wear debris play an important role in wearing.
   – Hard wear debris should be avoided such as oxide film formed during wearing by composition design

3. Formation of surface layer during wearing process may effectively improve the wearing resistance if

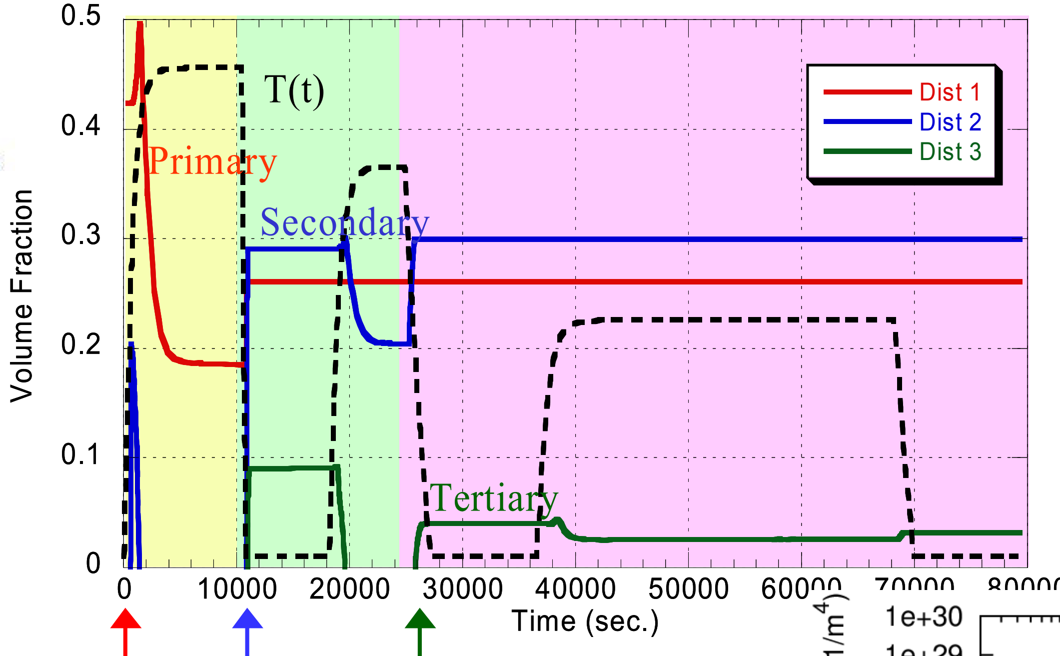
QuesTek PrecipiCalc Summary

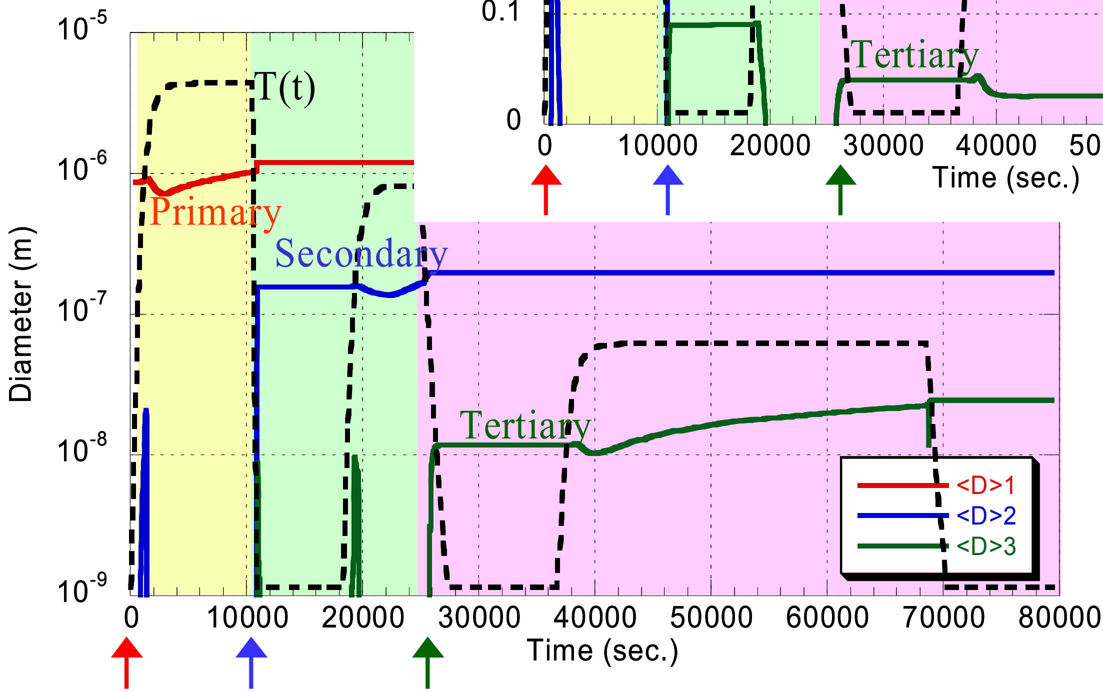
- Is developed for solving real material engineering problems, and is not a research tool for identifying new precipitation mechanisms or producing stunning microstructure pictures
- Is a software with Two-State Continuum Models for calculating the Multicomponent Precipitation Kinetics for Dispersed Phase(s).
- Contains mechanistic and hierarchical models Including: Steady state multicomponent homogeneous and heterogeneous nucleation model with non-isothermal transient (incubation), 3D multicomponent growth model using full diffusivity matrix.
- Places no constraint on temperature profile with a uniform treatment for isothermal and non-isothermal (both quench and heat up) conditions

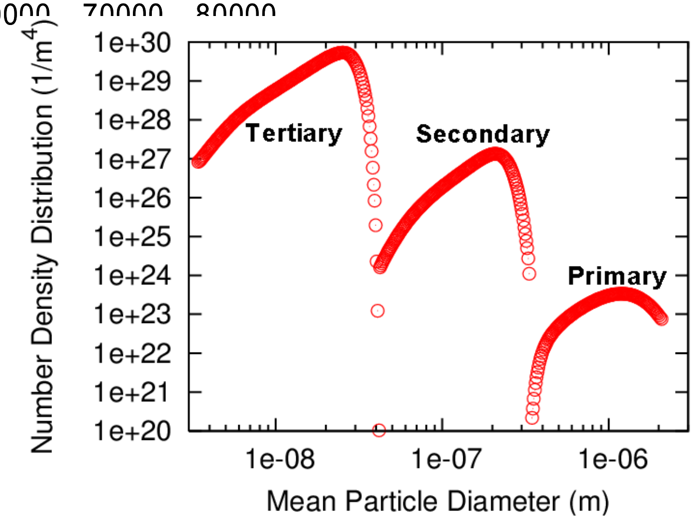
Implementation Overview of PrecipiCalc



PrecipiCalc Results for IN100 disk

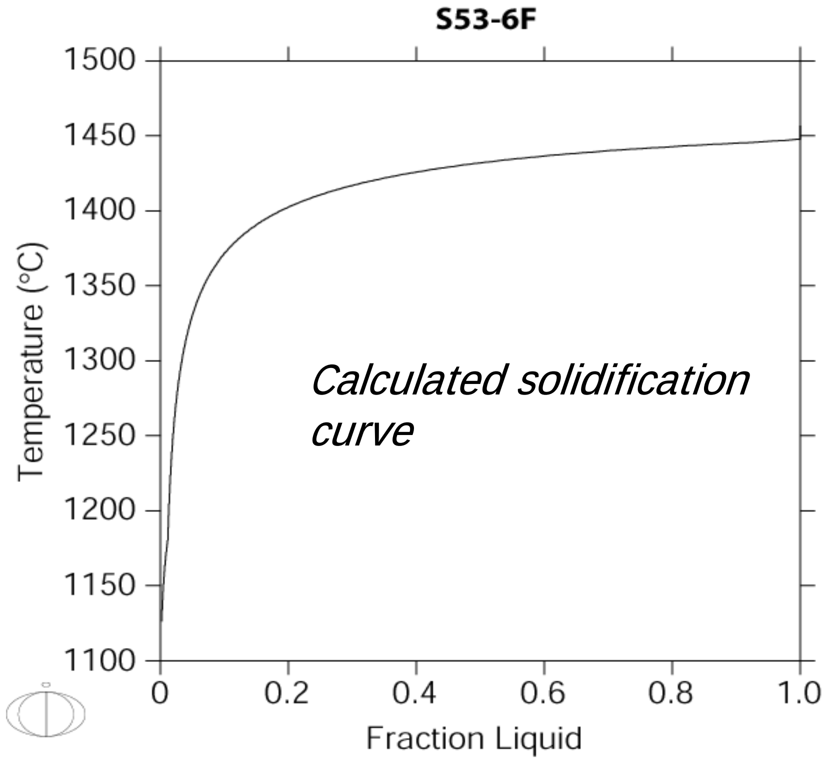


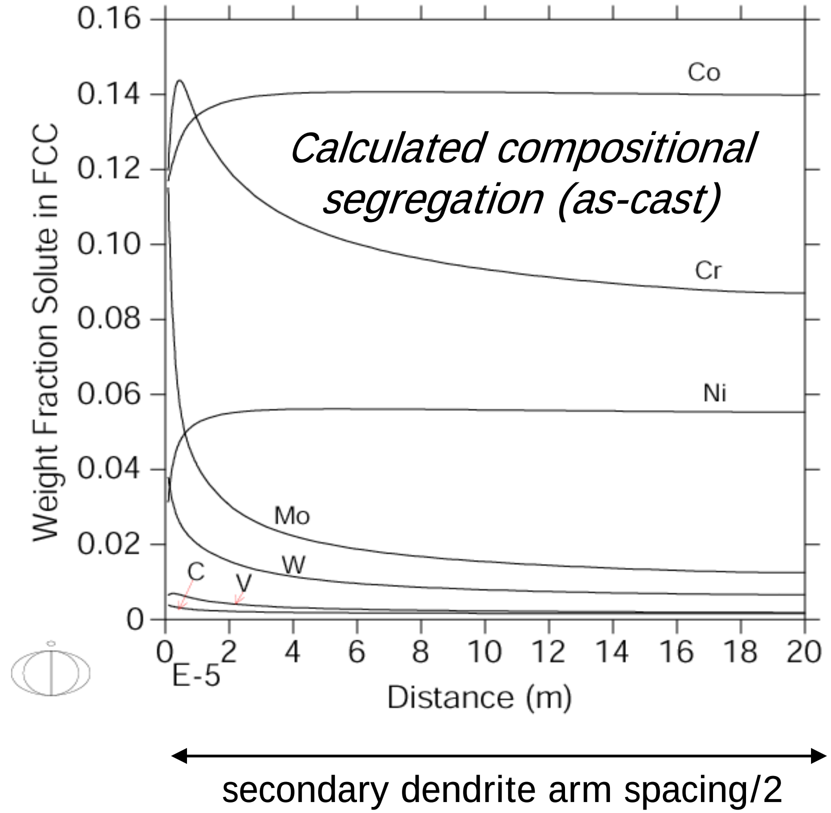




Moving Boundary Modeling of Solidification and Homogenization

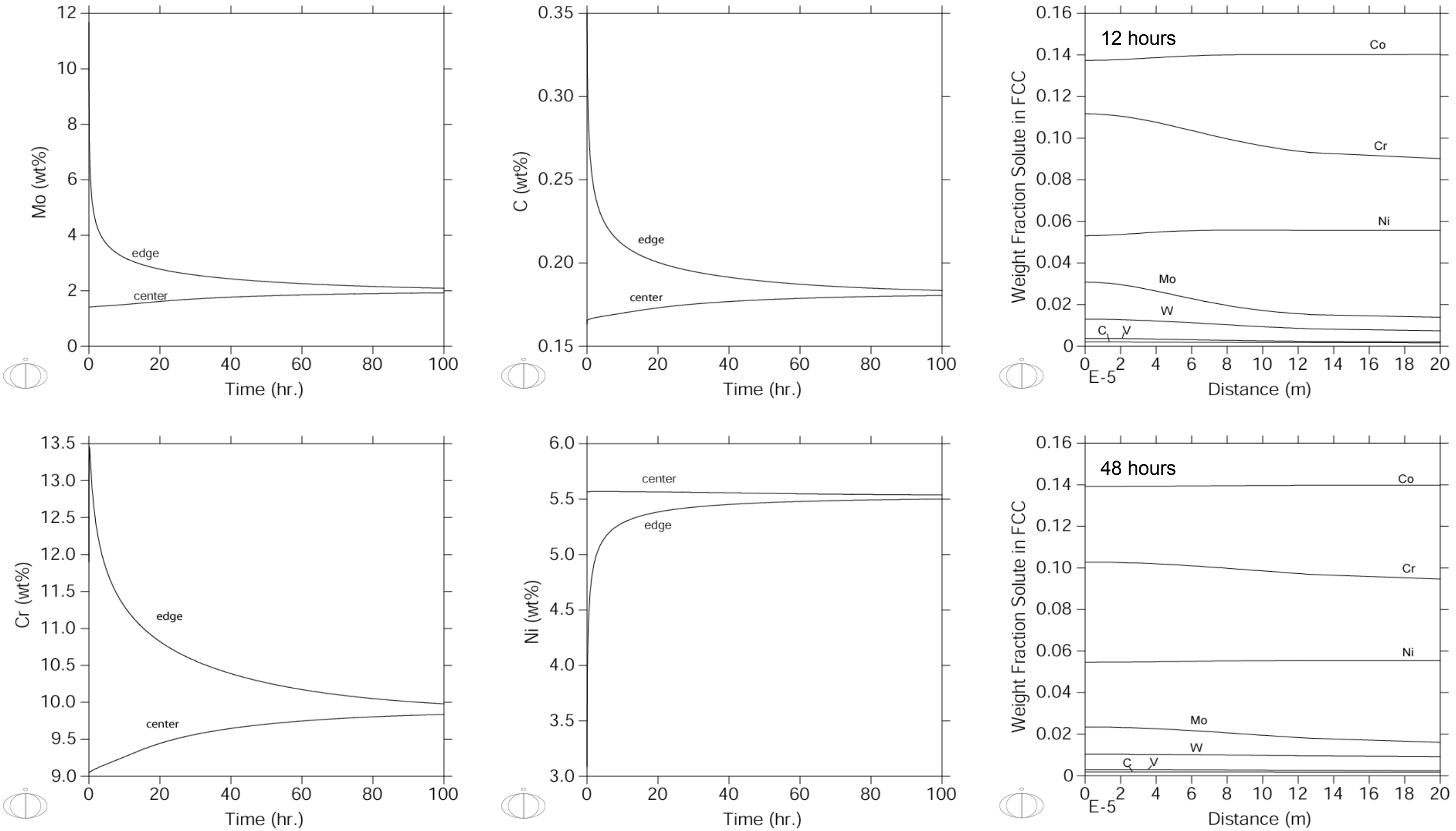
Example of QuesTek Ferrium® S53®





- CALPHAD-framework based software: DICTRA
- Moving boundary method which accounts for back-diffusion in the solid, and fast diffusion in the liquid

Homogenization Simulations
Example of QuesTek Ferrium® S53®



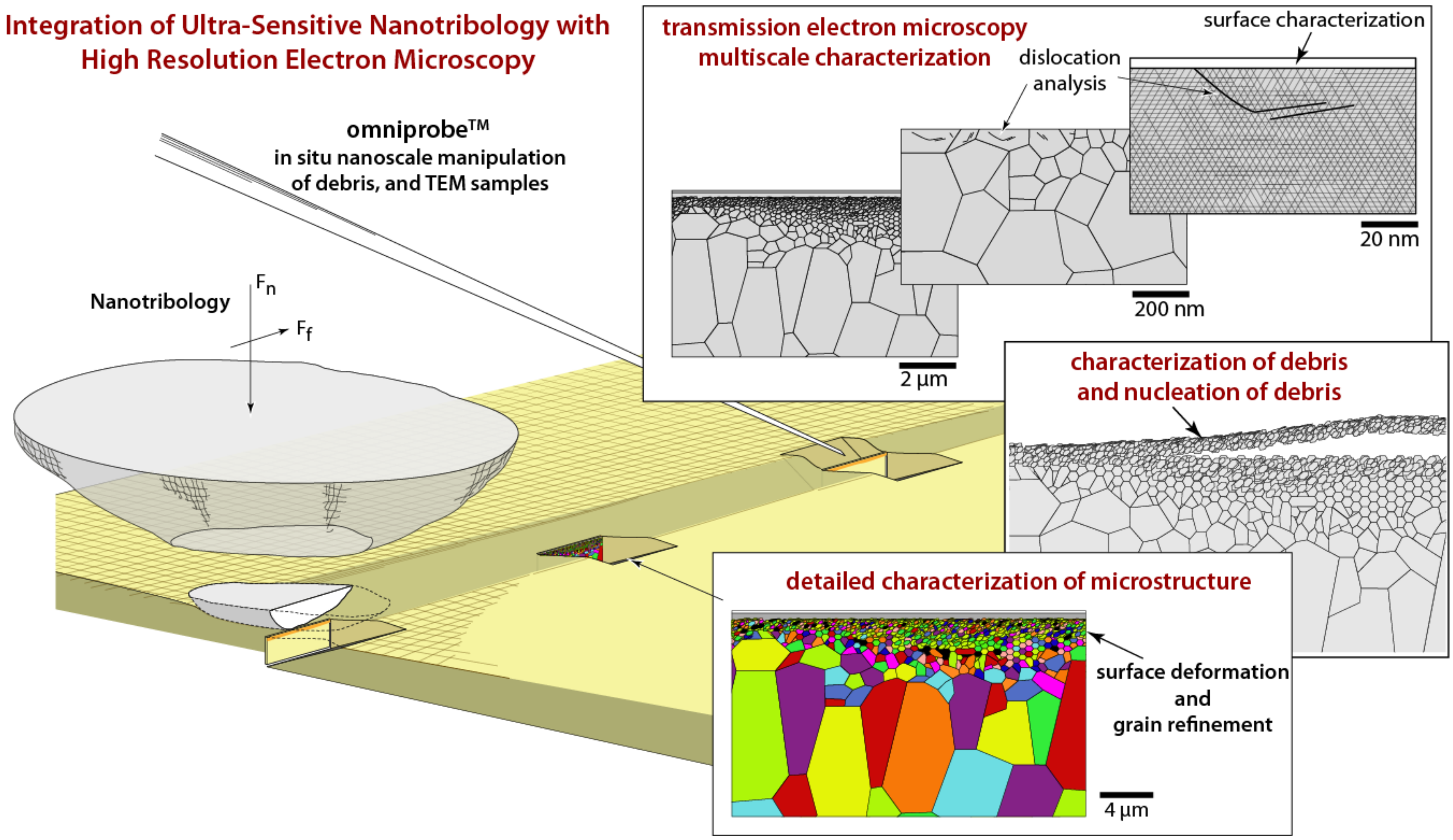
Ability to predict optimal homogenization time and temperature

QuesTek *Cuprium*™

Property comparison of QuesTek's *Cuprium* alloy with incumbent Cu-Be alloy and the leading alternatives

Property	Cu-Be (Cu-1.9 Be)	QuesTek Cuprium™	ToughMet® 3 (Cu-15Ni-8Sn)	BioDur® CCM (Co-Cr-Mo)
0.2 % Yield Strength	140 ksi (minimum) (non-CW)	133 ksi (typical) (non-CW)	107ksi (minimum) (non-CW)	85 ksi (non-CW) (typical)
Elongation	3 - 8%	~3 - 8%	3 – 10%	26%
Wear Ranking	3 (worst)	2	2	1 (best)
Cold workability	Good	Good (tensile)	Excellent	Excellent
Cold work required?	No	No	Yes	Yes
Hot workability	Good	Good (Gleeble)	Limited	Good
Melting Technique	Various techniques, limited Be suppliers	Standard CuNiSn processes to be pursued as initial processing path	Proprietary techniques: Equicast Osprey	VIM + ESR, limited suppliers

Wear Microscopy



Safety and Health Background

- Exposure to beryllium has been reported to produce a range of diseases including lung cancer and Chronic Beryllium Disease (CBD). Recent research and aerospace industry exposure incidents indicate the potential for disease at lower levels than OSHA's 8 hour TWA of 2 $\mu g/m^3$ Permissible Exposure Limit (PEL). OSHA issued a Hazard Bulletin in May 2002 recommending a lower limit of 0.2 $\mu g/m^3$ to prevent CBD. Additional protection is advised to prevent skin contact with dust.

- Chronic Beryllium Disease (CBD)
  - Primary exposure risk is Be dust or fume inhalation
  - ~ 4-10% of population show sensitivity to Be
  - Allergic type reaction in lungs creating fluid and scarring
    - Results in chronic steady decline of pulmonary function until death and/or increases lung cancer risk
    - CBD symptoms and progression can occur well after exposure
  - No Pre-exposure screening test available.
    - Current tests identify sensitized immune system post exposure
  - Mid to late 90s; Multiple studies conducted based on Manufacturer, DOE, other worker complaints
    - link CBD to exposure below current limit

Transition Plan

•A preliminary static properties design database as well as a comprehensive characterization of the tribological properties dataset will be developed.

• Sub-scale and full-scale bushing demonstrations will be executed throughout the progression of the proposed effort to ensure applicability of the technology in relevant loading conditions\operational environment.

• Compatibility with legacy structural alloys and mechanisms, as well as sealant, primer, topcoat and corrosion prevention protocols will be evaluated to ensure implementation.

• As an airframe integrator and design entity, Northrop Grumman is fully aware of the issues associated with alloy development and integration, and has also been open with its Air Force and Navy customers regarding the production and sustainment challenges associated with Cu-Be alloys.

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